

## **Requirements for Modeling and Simulation for Space Medicine Operations: Preliminary Considerations**

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### **1. Abstract**

The NASA Space Medicine program is now developing plans for more extensive use of high-fidelity medical simulation systems. The use of simulation is seen as means to more effectively use the limited time available for astronaut medical training. Training systems should be adaptable for use in a variety of training environments, including classrooms or laboratories, space vehicle mockups, analog environments, and in microgravity.

Modeling and simulation can also provide the space medicine development program a mechanism for evaluation of other medical technologies under operationally realistic conditions. Systems and procedures need preflight verification with ground-based testing. Traditionally, component testing has been accomplished, but practical means for "human in the loop" verification of patient care systems have been lacking. Medical modeling and simulation technology offer potential means to accomplish such validation work.

Initial considerations in the development of functional requirements and design standards for simulation systems for space medicine are discussed.

### **2. Introduction**

The National Aeronautics and Space Administration (NASA) is a world leader in the development and use of simulation technologies for training, procedure development, and validation of complex systems. The Johnson Space Center (JSC) is the lead center for NASA's Human Exploration and Development of Space Enterprise. This lead center role includes responsibility for the design, development, and testing of spacecraft and systems for humans; selection and training of astronauts; planning and conduct of human space flight missions; and responsibility for medical support, systems engineering, and many scientific experiments.

The JSC Space Medicine and Health Care Systems Office has operational responsibilities for implementing medical support for NASA's human space flight program. As the managers and users of medical care systems for space flight, JSC space medicine specialists have the primary responsibility within NASA for the definition of operational medical requirements, medical procedures, specifications of medical



hardware and systems, and their support. Within this context, the JSC Space Medicine program is now developing plans for more extensive use of high-fidelity medical simulation systems.

Astronaut Crew Medical Officers (CMOs), supported by flight surgeons in the Mission Control Center (MCC), provide the routine and emergency medical care to astronaut crews during space flights. CMOs—who are generally not physicians—are trained to perform diagnostic and therapeutic procedures. The Shuttle Orbiter Medical System (SOMS—for Space Shuttle flights) and the Crew Health Care System (CHeCS—for International Space Station) include medical and surgical supplies for on-orbit health care. The CHeCS Health Maintenance System (HMS) includes components for in-flight preventive, diagnostic, and therapeutic medical care.

At present, evacuation to a definitive care medical facility is planned if serious injury or illness occurs on orbit, but there may still be a delay of up to 24 hours between the evacuation decision and arrival at the definitive medical care facility (perhaps longer, in some circumstances). In the interim, CMOs will be responsible for the evaluation, initial resuscitation, stabilization, and monitoring of the patient until landing.

The medical plans for in-space resuscitation and emergency care have been developed and refined over the past two decades of the Space Shuttle program. The more expanded capabilities planned for the International Space Station (ISS) have built on this foundation of experience, supplemented by operational experience from the Shuttle-Mir program.[1] Operational medical capabilities are expected to evolve and the ISS will become a test-bed for the development and validation of medical systems that will support human exploration missions beyond Low Earth Orbit (LEO).

Modeling and simulation have been recognized as important programmatic components for Space Medicine. Medical training competes with many high priority activities that are part of astronaut mission preparation. Sophisticated medical simulation devices have demonstrated value as training aids for medical care personnel in academic and military applications. Current training systems utilized by the JSC Space Medicine program are limited by amount of training time available and limited medical background knowledge of non-physician CMOs. The use of high fidelity simulation is seen as means to more effectively use the limited training time available.

Integration of high-level medical simulators in NASA's clinical space medicine development program can also provide a mechanism for evaluation of other NASA technologies in operationally realistic conditions. For example, augmented reality systems can add fidelity to the simulation environment, utility of telemedicine systems in critical intervention scenarios can be tested, and new noninvasive sensor technologies can be validated with complex physiologic models. The portability of currently available simulator systems make possible their use in operationally-relevant environments, including the Crew Return Vehicle (CRV) for the International Space Station (ISS), the ISS mockup, and in microgravity (such as during KC-135 parabolic flight). Several approaches to medical modeling and simulation have been used (Table 1), but none features ideal for all applications.



Table 1

<b>Approaches to Medical Modeling and Simulation</b>	<b>Features</b>	<b>Current Shortcomings</b>	<b>Examples</b>
<i>PC-based interactive multimedia training systems</i>	Inexpensive, readily available, portable	Inconsistent standards, less suitable for task training	Trauma Patient Simulator™ (Research Triangle Institute)
<i>Digitally Enhanced Mannequins</i>	Commercial-off-the-shelf technology, suitable for team training	Limited stand-alone capability, more complex and expensive than PC-based platform	Human Patient Simulator™ (METI)
<i>Virtual Workbenches</i>	Rapid technical development, facilitates practice of minimally invasive surgical procedures and team training	Limited stand-alone capability, haptic feedback limited by current technology, less portable than PC-based system	ImmersaDesk™ (Fakespace)
<i>Total Immersion Virtual Reality (TIVR)</i>	Evolving technology, provides realistic environmental simulation	High development costs, requires support systems and larger facility	University of Michigan Cave Automated Virtual Environment (CAVE)
<i>Comprehensive Computational Models Combining Function and Structure</i>	Integrated modeling of human systems, from molecular to system level; predicts problems, simulates responses to countermeasures or interventions	Integrated models proposed, but do not yet exist; high development costs anticipated	"Digital Human" National Biomedical Research Institute (NSBRI), Integrated Human Function Team  "Virtual Human" Oak Ridge National Laboratory, Life Sciences Division

### 3. Medical Risks in Space Flight

The risk of significant medical problems occurring during long duration (>30 days) mission in LEO have been estimated from past operational experience.[2] Data were compiled from U.S. and Russian space flight data, the JSC Astronaut Longitudinal Study of Astronaut Health, experience from crews of U.S. Navy nuclear submarines, health information from Antarctic winter-over personnel, and military aviator populations. "Significant" was defined as a problem that would normally require evacuation, an emergency room visit, or hospital admission (as applicable in the operational environment). Based on this compilation, the risk of a significant occurrence was estimated as 0.06 to 0.07 per person-year. The subset requiring advanced life support was estimated as 0.02 per person-year. This implies that there may be two to three medical evacuations required during the 15-year operation lifetime of the ISS.



There are a number of physiologic responses and adaptations that occur during space flight. The principal known physiologic effects of space flight are due to microgravity. These include cardiovascular alterations, bone demineralization, muscle alterations and atrophy, neurovestibular adaptation, human performance factors, and effects on sleep and chronobiology.[3,4] Some factors, while relevant to missions in LEO, are of particular concern when considering future potential missions that would take crews beyond LEO. These missions are likely to be lengthy, with prolonged delays in evacuation to terrestrial medical care. Radiation in deep space—beyond the Earth's protective magnetosphere—is of greater concern. Not only is there electromagnetic radiation (x-rays), but there are also risks from Galactic Cosmic Radiation (GCR), which is primarily composed of high-energy heavy ion particles (HZE), and Solar Particle Events (SPEs).[4-6]

Clearly, the CMO must be robustly trained, but there is no reasonable way to train for all possible scenarios. Also, skills and knowledge degrade over time. Therefore, it is accepted that there will be a need for refresher or "just-in-time" training during a long duration exploration mission. The pre-flight and in-flight training systems must consider expected illnesses and ambulatory medical problems, acute medical emergencies that could occur in space, and some types of chronic disease. (Table 2)

Table 2

#### **Expected Illnesses and Ambulatory Medical Problems**

- Orthopedic and musculoskeletal problems
- Infectious, hematological, and immune related diseases
- Dermatological, ophthalmologic, and ear/nose/throat problems

#### **Acute Medical Emergencies in Space**

- Wounds, lacerations, and burns
- Toxic exposure and acute anaphylaxis
- Acute radiation illness
- Dental emergencies
- Ophthalmologic emergencies
- Psychiatric emergencies

#### **Chronic Diseases**

- Radiation induced problems
- Responses to environmental exposures, including lunar or planetary dusts
- Presentation or acute manifestation of nascent illness

#### **4. Space Medicine Operational Constraints**

The practice of space medicine must contend with environmental and programmatic challenges.[5,6] The mass, volume, communication bandwidth requirements, and power consumption of medical systems must be optimized, as they compete with vehicle and payload systems. Communication capabilities will be constrained, both now and in the future. The orbital track and configuration of the ISS causes it to be out of direct communication with Mission Control Center 45-50% of the time.

Operational features of future exploration missions will require CMOs to function with even greater autonomy. Communication latency due to the great distances involved



will prohibit real-time communication and remote operation of critical medical systems. For example, there is 7-40 minute round-trip communication to Mars. Relative positions of the Earth, Sun, and Mars may impose communication blackouts for up to 30 days. Medical systems must contend with bandwidth limitations, but these challenges may be mitigated by future technological advances, such as the establishment of interplanetary internet or broadband optical communication links.

There are many constraints imposed by distance. Without resupply capability, all consumables must be carried on board or generated *in situ*. Drugs and similar items need long shelf-lives. Device failure risks should be minimized by the use of highly-reliable systems, built-in fault management, functional redundancies, or by allowing astronaut servicing. Additionally, the long transit times of exploration missions impose physiological and psychological stresses due to the prolonged isolation and confinement. These factors may have effects on human performance and should be considered in the design of medical care systems.

Crew time, however, remains one of the space program's most precious and limited resources. This means that CMO training time is severely restricted. During the several years of preparation for an ISS mission, astronauts receive less than three weeks of medical training. (Table 3) Also notable, is that in NASA's current operational paradigm, there is no specialized training or proficiency maintenance program for the subset of astronauts who are physicians. While a graduate medical education program specific to in-flight space medicine practice has been envisioned [7], no such program exists. Thus, it is an imperative to optimize the limited medical training time available. The use of medical modeling and simulation technology is recognized as one means to achieve this goal.

Medical operations must be an integrated part of the overall mission. All systems for space flight must meet specific design, safety, and operational requirements. Not only must hardware items, software, and procedures be tested individually to be certified for flight, each component needs to be verified as a functional part of the overall system. The standard yardstick is to perform end-to-end testing in the "as flown" configuration.

Medical systems and procedures need preflight verification with ground-based testing. Traditionally, component testing has been accomplished, but practical means for "human in the loop" verification of patient care systems have been lacking. Medical modeling and simulation technology offer potential means to accomplish such validation work.



**Table 3 Medical Training Schedule for International Space Station Crew Members**

<b>Topic</b>	<b>Schedule</b>	<b>Hrs</b>	<b>Self-Study</b>	<b>Lecture</b>	<b>Discussion</b>	<b>Hands-On</b>	<b>Video</b>
<i>Field Medical Training</i>	L-24/36 months	72	X	X	X	X	
<i>ISS Space Medicine Overview</i>	L-18 months	0.7	X	X	X		
<i>Toxicology Overview 1</i>	L-18 months	0.7	X		X		
<i>Medical Equipment Computer Overview</i>	L-12 months	0.5		X			
<i>Countermeasures Systems Evaluation Operations</i>	L-6 months	2.5	X			X	
<i>Dental Procedures</i>	L-6 months	1				X	
<i>ISS Medical Diagnostics</i>	L-6 months	5				X	
<i>ISS Medical Therapeutics</i>	L-6 months	6				X	
<i>Behavioral Medicine Issues</i>	L-4 months	1		X	X		
<i>ISS Medical Evaluation of Decompression Sickness</i>	L-4 months	1		X		X	
<i>ISS Cardiopulmonary Resuscitation</i>	L-4 months	2.5	X	X		X	X
<i>Advanced Cardiac Life Support</i>	L-4 months	18	X	X		X	
<i>Toxicology Overview 2</i>	L-3 months	0.5		X	X		
<i>Medical Refresher</i>	L-2 weeks	1					
<i>CMO Computer Based Training</i>	Onboard	1/mo					CBT
<i>CHeCS Health Maintenance System Contingency Drill</i>	Onboard	1				X	

Abbreviations: "L-" = time before launch

CBT = Computer Based Training

CMO = Crew Medical Officer

CHeCS = Crew Health Care System

## **5. Current "Real World" Applications of Modeling and Simulation: The ISS Era**

The goals for ground-based simulation training include familiarization with medical systems and procedures, critical incident response, and team training. In the short term, high fidelity medical simulation systems should be incorporated into astronaut CMO and flight surgeon training. Currently available systems facilitate practice of individual



psychomotor skills and have features that are adaptable to various levels of trainee knowledge and experience. Potential applications include things such as part task training for basic CMO skills (orientation to medical kit use, patient assessment, airway management, procedures, etc.), Advanced Cardiac Life Support (ACLS) certification training for astronaut-physicians and flight surgeons, ACLS familiarization training for biomedical flight controllers, and to provide proficiency training for crewmembers who have completed the Field Medical Training (Emergency Medical Technician-Basic) course.

Simulation is not viewed as a replacement for clinical practice, rather, as a means to enrich limited clinical experiences. Unusual scenarios can be modeled, allowing emergency procedures to be drilled.[8,9]

This approach parallels aviation training, with which all astronauts are familiar. Aviators must be proficient in responses to in-flight emergencies. Some actions must be drilled and practiced, so they can be accomplished immediately, without consulting reference materials. Emergency procedures checklists start with "bold face" immediate action items that must be memorized and drilled. They can then proceed with follow-on actions that can be completed with less time pressure, consulting and following the standardized checklist. If a medical emergency presents with a life-threatening problem, the CMO should be proficient in any "bold face" immediate action responses that would be necessary to stabilize the situation. As it would take some time to consult a checklist or call the ground-based flight surgeon, medical training must be sufficient for the responding CMO to complete time-critical emergency interventions without direction.

Risk assessments suggest that in-flight medical events that would require immediate life-saving intervention will be extremely uncommon. Still, the CHeCS medical kits and the associated CMO training are designed to provide for resuscitation and stabilization, should such an event occur. Considering the baseline health of the crews, age and gender factors, operational or environmental risks, past experiences from space flight or operations in analogous environments, and other relevant data, the most likely scenarios that might require such intervention can be anticipated. These include:

- acute airway obstruction
- decompression sickness with severe central nervous system impairment or circulatory compromise
- intracavitary or gastrointestinal hemorrhage
- major thermal or electrical injury
- myocardial infarction
- pneumothorax
- pulmonary embolism
- respiratory failure due to aspiration or inhalational injury
- sepsis
- severe anaphylaxis
- stroke or closed head injury
- unstable supraventricular tachycardia



Medical team Crisis Resource Management training has been developed as an analog to courses in aviation Crew (or Cockpit) Resource Management (CRM).[8,9] This type of training has been found to be especially useful for medical professionals as they transition to more complex roles and settings, such as resident anesthesiologists learning to manage critical incidents in the operating room. The incorporation of CRM principles into CMO training naturally follows. This is also consistent with NASA's emphasis on effective team coordination and performance. As the ISS has multinational and multicultural crews, team training is of particular value to minimize miscommunication due to cultural nuances.[10] CMO participation in high-fidelity medical simulations provides another opportunity to reinforce CRM principles.

## **6. Desired Features of Simulation System for Training Applications**

While many training requirements of the space medicine program are conventional, there are some mission-specific requirements that should be considered.

The need to model microgravity effects is the most unique requirement for space medicine training applications.[5,11] Microgravity is known to alter cardiovascular physiology, autonomic function, fluid distribution, mineral metabolism, pharmacokinetics, pharmacodynamics, and other functions. Clinically significant effects on immune function and wound healing are suspected. Microgravity effects on fluid distribution also have effects on the presentation and course of certain conditions. For example, free fluid (such as might occur with an intraabdominal abscess) will not tend to localize in dependent locations. Fluid drainage may be a problem. Paranasal sinuses, as another example, will not have dependent drainage and suppurative sinusitis may be more of a risk with upper respiratory tract infections during space flight.

Training systems should be adaptable for use in a variety of training environments. These include classrooms or laboratories, space vehicle mockups, analog environments (such as field training settings, or in the BIO-Plex, a long-term closed habitat being constructed at JSC for research in advanced life support systems). Systems should also function in microgravity, to support medical training in the KC-135.

General characteristics desired include portability (manageable size, weight, and logistic support requirements); ability to function in various environments (tolerance of moisture, vibration, changes in temperature and barometric pressure); adaptability (usable for a variety of training objectives) and safe operation (no hazards to users and operators, and no interference with other critical systems).

## **7. Simulation for Evaluation of Medical Devices and Procedures for Space Flight**

Medical modeling and simulation tools have other applications, in addition to use for training, that are relevant to the JSC Space Medicine and Health Care Systems office mission. Other candidate uses include evolution and validation of new on-orbit medical procedures and for evaluation of on-orbit medical equipment human factors (design verification and validation).



Scenario-based simulations provide a valuable tool for evaluating capabilities and identifying deficiencies in the medical infrastructure, as well as for the validation of clinical procedures and equipment. Clinical scenarios, developed from published literature or operational experience and model the presentation and time course of patient conditions, provide means for testing many aspects of the medical care delivery system, including training, equipment, communication, and other relevant factors. Better documentation of standards of care for each patient condition, along with the identification of new care procedures for each condition, result.

JSC, partnering with industry, military medicine, and the academic community (through the National Space Biomedical Research Institute), and others, is targeting integration of a new generation of smart medical devices into an advanced version of the ISS Crew Health Care System. The envisioned networked device array will provide a simplified user interface to assist on-orbit care providers who must manage both the patient and the supporting medical technologies being used. A fully evolved system should provide (1) a single scaleable user interface for monitoring, controlling, documenting and guidance; (2) interactive context-sensitive diagnosis and management checklists; (3) integrated medical data storage and downlink capability; and (4) plug-and-play medical device modularity.

## **8. Long-Term Vision: Applications of Medical Modeling and Simulation**

Exploration missions beyond LEO will require a level of autonomy far beyond that of the human space flight experience of the 20<sup>th</sup> century.[11] While it is difficult to project the state of technology in the future decades when humans may venture beyond Earth's neighborhood, a consensus of opinion of operational space medicine experts has identified desirable features of medical systems. In particular, future on-board medical devices should have:

- non- or minimally invasive approaches for diagnosis and treatment
- built-in, distributed intelligence and automation (smart medical systems)
- capabilities for consultative, diagnostic, and therapeutic telemedicine (store and forward)
- assistive technologies
- intuitive interfaces
- reconfigurable interfaces and level of support that can accommodate the skill and medical training level of various crew members
- comprehensive user support and feedback
- minimal mass, volume, power needs
- high degree of reliability, to ensure function throughout mission

Systems should be maintainable, upgradeable, and reconfigurable. They should be multi-functional. Ideally, the systems that support crew medical care should be adaptable to non-medical applications.



## 9. Initial Plans for Modeling and Simulation Use in Space Medicine

The JSC space medicine programs is now taking the following steps:

- Identification of potential collaborators for development of simulator-based clinical training program for use by JSC personnel.
- Developing initial recommendations for how to use medical simulators in training of Space Shuttle CMOs, ISS CMOs, flight surgeons, and others.
- Identifying clinical training experiences that best complement simulator training.
- Identifying and prioritizing candidate technologies to be evaluated for use in medical simulator training.
- Definition of human factors issues in the design and implementation of CMO medical simulator training programs.
- Identify tasks for the NSBRI.
- Establish protocols and procedures for optimal use of simulation facilities

Dialogue and collaboration are sought.

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